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Energy and Resource Efficiency of Laser Cutting Processes

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Abstract

Due to increasing energy and resource costs at the one hand and upcoming regulations on energy and resource efficiency at the other, a growing interest of machine tool builders in the environmental performance of their machine tools can be observed today. The last decade, academic as well as industrial research groups started to assess the environmental aspects of discrete part manufacturing processes and indicated a significant potential for improvement [1]. This paper provides an overview of the environmental performance (energy and resource efficiency) of different types of laser cutting systems and derived performance improving strategies.

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Keywords: Laser Cutting; Energy and Resource Efficiency; Environmental Impact; Sustainable Production

1. Introduction

Taking into account the expected growth of the world's population and increasing welfare level in developing countries, the global energy and material resource demand can be expected to increase significantly. Therefore, the environmental burden per unit produced should be strongly reduced in order to assure a sustainable impact level [2-3]. Consuming around 25% of the total energy in Europe [4], the manufacturing industry is responsible for a substantial part of the total environmental impact and this impact can be expected to further increase taking into account the trend towards more energy intensive processes [5]. Bey et al. (2013) indicated that the main barriers for implementation of environmental strategies in companies are a lack of information on environmental impacts, lack

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of expert knowledge as well as a lack of allocated resources (man power and time). On the other hand, the most important drivers, both for triggering and sustaining implementation of environmental strategies in companies, are legislative requirements, customer demands and expected competitive advantages [6]. In order to deal with the lack of thorough environmental analysis and related identification of improvement potential, the CO_2PE! – Cooperative Effort on Process Emissions in Manufacturing – initiative [7] has been launched in 2009 and has as objective to coordinate international efforts aiming to document and analyse the overall environmental impact for a wide range of available and emerging manufacturing processes and to provide guidelines to improve these.

Life cycle inventory data collection methods

Different methods - starting from theoretic calculations until detailed process measurements and analysis - exist to determine the energy and resource consumption of manufacturing processes. While Abele et al. (2005) describe theoretic equations to calculate the energy and resource consumption for a wide range of production processes [8], Overcash et al. (2009) propose a generic methodology to gather unit process life cycle inventory data using rules of engineering and industrial practice [9]. Within the CO_2PE!-Initiative, Kellens et al. (2012) developed a methodology for systematic analysis and improvement of the impact of manufacturing unit processes [10]. Finally, part two of the emerging ISO 14955 standard on environmental evaluation of machine tools provides guidelines how to measure and quantify the energy demand and efficiency of machine tools in line with this methodology [11]. A comprehensive comparison of the previously mentioned methods as well as the available life cycle inventory (LCI) data in commercial LCI-databases is provided by Duflou et al. (2012). The authors observed large discrepancies on the energy demand and related environmental impact of discrete part manufacturing processes obtained by different assessment methods. While theoretical calculations often result in large underestimations, most energy values for manufacturing processes specified in commercial LCI databases show significant space for improvement [12].

1.1. Laser cutting systems

Laser cutting is the most common industrial application of lasers and a well-established manufacturing process. The high material versatility, edge quality, accuracy and production flexibility combined with a high material utilization and virtually no tool wear are just some of the advantages that make it a desirable technology in comparison with other conventional or non-conventional cutting methods [13-14]. A laser cutting system is primarily defined by the type of laser source used to generate the laser beam. CO_2 laser sources are still most used for industrial sheet metal cutting. This is a well-established technology where the process has been pushed to its limits. Current research mainly focuses on real-time process monitoring and control [15] and on increasing machine tool efficiency [16] as methods to enhance this technology. High power fiber and disk lasers have been introduced in the last decade as a reliable alternative to the CO_2 sources due to the increased wall-plug efficiency and the better beam absorption behavior in highly reflective metal sheets. With a wavelength ten times shorter than CO_2 and with similar laser quality the focusibility is much higher. This allows enough energy density to achieve very high cutting speeds in fusion cutting of thin metal sheets, up to 3 times higher than a typical CO_2 source with the same output power [17]. Although this drastically reduces operational costs for these specific conditions, at higher thicknesses ($\geq$ 4 mm), the surface quality is much worse compared to the CO_2 technology. The last decade, several researchers have been working in order to understand and control this effect [18-20], but currently CO_2 still achieves the best results for thicker sheets. In laser cutting with reactive gases there is no strong difference in cutting performance or cutting quality between different laser sources with similar output power [17]. Thus, the most economic option for a laser machine tool depends strongly on the materials and thicknesses to be cut. More recently, Direct Diode Lasers (DDL) are being introduced as a new generation of sources suitable for sheet metal cutting. In the past years, developments achieved for micro-optic manufacture techniques [21-22] and beam combining strategies [23-25] were responsible for the necessary increase in energy density to extend the application range of this technology to more demanding laser cutting applications. The first theoretical and experimental studies regarding this topic were recently published [26], revealing the high potential of this technology for decreasing operational costs in laser cutting of sheet metal. The diode lasers are more efficient, more compact, wavelength versatile and are easily adapted to automated production (lower investment price) making them a strong competitor for the previous described technologies. Table 1 summarizes the benefits, drawbacks and application range for the above mentioned laser cutting technologies.

From environmental point of view, CO_2 laser cutting processes were analysed by Duflou et al. (2010), Oliveira et al. (2011) as well as Kellens et al. (2012). In addition to energy consumption, the assist gasses (e.g. nitrogen and oxygen) and generated process waste were also found to contribute significantly to the total environmental impact of CO_2 laser cutting processes [27-29]. Electrical power analyses of fiber and diode laser cutting machine tools are provided by Kellens (2013) and Rodrigues et al. (2013) [17, 30]. More detailed descriptions of the environmental performance and improvement potential of laser cutting processes are provided in Sections 2 and 3 respectively.

Table 1. Characteristics of different generations of laser sources used for sheet metal cutting.

	1st generation **CO_2**	2nd generation **Fiber and Disk**	3rd generation **Direct diode**
Radiated wavelength	10,6 µm	1,06 µm	808 nm – 1550 nm
Efficiency	5 – 10%	20 – 30%	30 – 40%
Benefits	- Relatively low purchasing cost	- Fiber guided - Efficient - High beam quality - Lower maintenance - High speed for fusion cutting of thin sheets	- Fiber guided - Highest efficiency - Lower maintenance - Compact - Wavelength flexibility - Relatively low purchasing cost
Drawbacks	- Mirror guided - Low efficiency	- Lower surface quality for thick fusion cutting - High purchasing cost	- Lower surface quality for thick fusion cutting - Wavelength range
Application range (cutting)	- **Metals** (steel and some aluminium alloys) - **Non-metals** (Plastics, glass, paper, fabric, woods, polymers)	- **Metals** (steel and aluminium alloys) - **High reflective metals** (copper, brass and gold)	- **Metals** (steel and aluminium alloys) - **High reflective metals** (copper, brass and gold)

2. Environmental performance of laser cutting processes

Kellens (2013) provided a comprehensive overview of the energy and resource consumption as well as related environmental impact of a wide range of CO_2 laser cutting machine tools [17]. Figures 1, 2 and 3 show respectively the input power profiles of 4kW CO_2, 2kW fiber and 1.85kW diode (test setup) laser cutting machine tools operated during different production modes. Figure 4 represents the power input at maximum capacity (cutting at maximum output power) for a set of 53 commercially available CO_2 and fiber laser cutting machine tools of 6 leading brands. While observing a relatively large difference in energy demand between machine tools with similar maximum capacities, a linear increase in input power demand can be observed for larger output powers. Furthermore, fiber and disk laser systems have a comparable energy demand, which is approximately 50% lower compared to their equivalent CO_2 alternative.

Within Table 2, an overview is provided of all relevant life cycle inventory data of the use phase of 2.5kW, 4kW and 6kW CO_2 laser cutting machine tools. Based on the 4kW data, Figure 5 (left side) shows the environmental impact distribution, calculated using the ReCiPe Endpoint Europe H/A life cycle impact assessment method, caused during the production of the nesting (stainless steel, sheet thickness 1mm) shown in Figure 5 (right side). Besides energy consumption (~68%), also the assist gas (~11%) and generated waste material (~20%) have a relevant contribution to the environmental impact. Direct process emissions and other consumables, including spare parts, have a rather limited contribution.

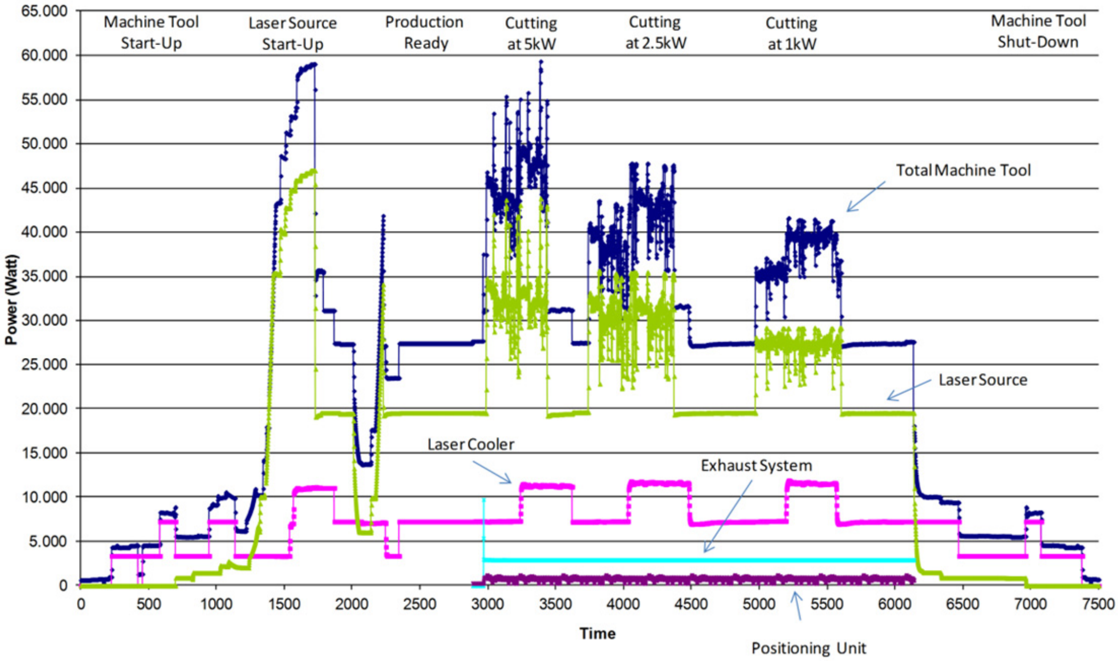


Fig. 1. Power profile of a 4kW CO_2 laser cutting machine tool.

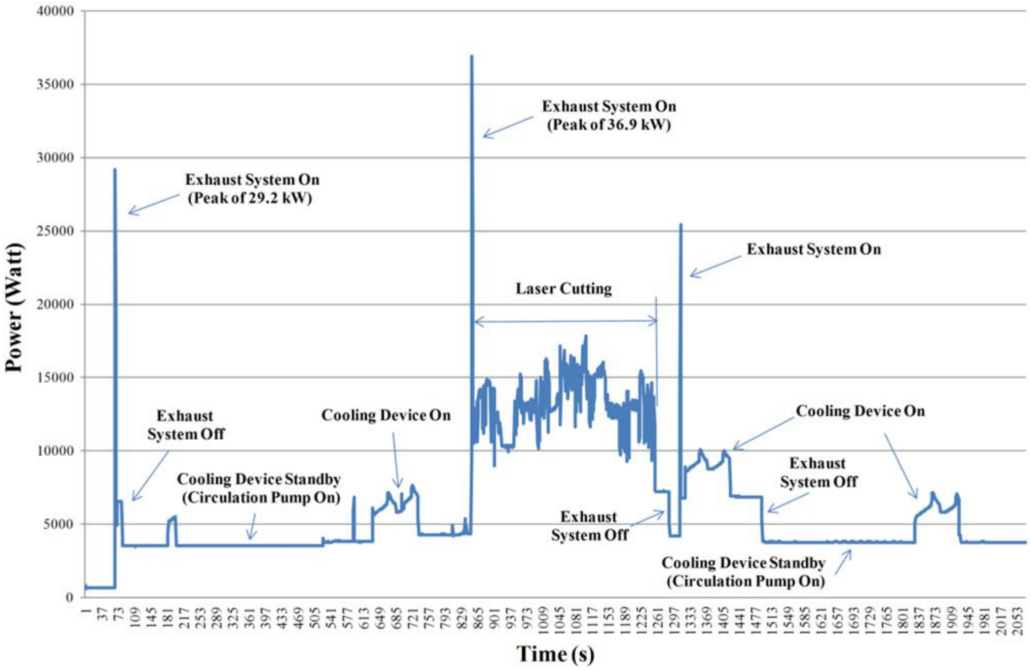


Fig. 2. Power profile of a 2kW fiber laser cutting machine tool.

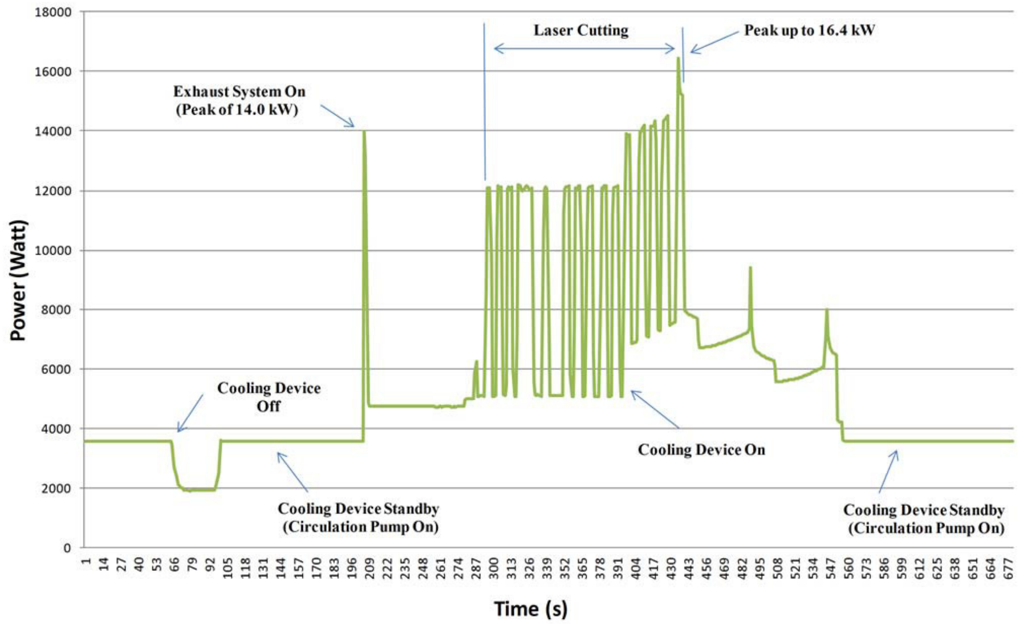


Fig. 3. Power profile of a 1.85kW diode laser cutting test setup.

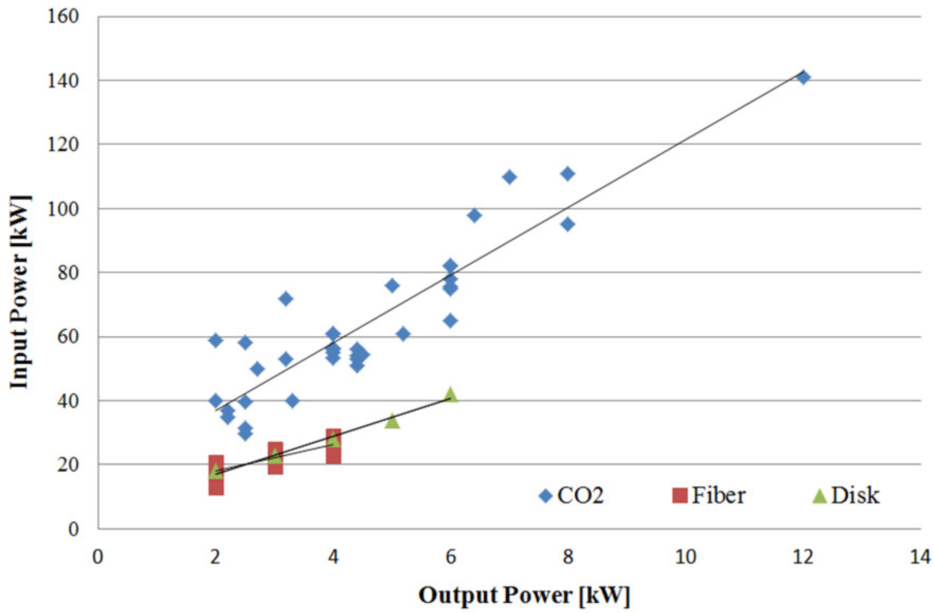
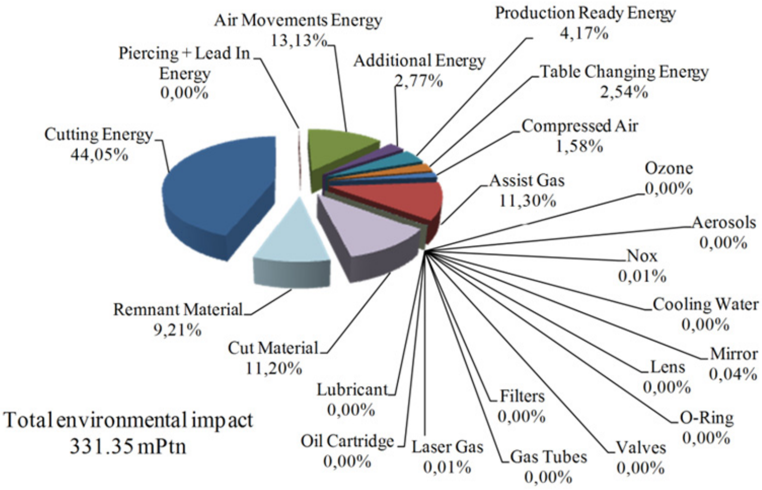


Fig. 4. Input power demand at maximum capacity for 53 different commercial available laser cutting machine tools.

Table 2. Life cycle inventory data for the use phase of 2.5kW, 4kW and 6kW CO_2 laser cutting machine tools.

	CO_2 Laser Cutting	**2.5 kW**	**4 kW**	**6 kW**
ELECTRICAL ENERGY	Cutting energy [kWh]	31.42	55.22	74.89
	Production ready [kWh]	1.64	2.98	3.64
	Table changing [kWh]	1.00	1.81	2.21
CONSUMABLES	Cutting gas - N_2 [l]	28.12	20.31	19.33
	Laser gas [l]	10	10	20
	Cooling water [l]	0.13	0.13	0.2
	Compressed air [m³]	5.4	5.4	8.1
	Regularly replaced parts (spare parts)	Mirror, lens, O-ring, lubrication oil, filters, Gas tubes and valves		
DIRECT PROCESS EMISSIONS	Aerosols [g]	45.0	72.0	108.0
	NO_x [mg]	201.6	324.0	486.0
	Ozone [mg]	21.6	36.0	54.0



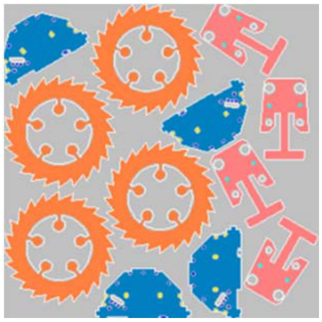


Fig. 5. Distribution of the environmental impact (left) for the production of the nesting (right).

3. Environmental impact improvement potential

Different strategies can be considered while aiming for the reduction of the energy and resource consumption and related environmental impact at a unit process level. Kellens (2013) proposed a generic improvement categorization starting from three main categories: proper process and machine tool selection; optimized machine tool design; as well as optimized process control [17]. While the first and last category are mainly controllable by the process planner or the machine tool operator, the original equipment manufacturer (OEM) or machine tool builder has a dominant influence on the machine tool design. Connected to these three main categories, thirteen sub-categories, shown in Figure 6, can be identified. Interrelationships between different sub-categories are indicated as dashed lines. Starting from the generic categorization of improvement measures shown in Figure 6, this paragraph describes some examples of quantified improvement measures for laser cutting processes.

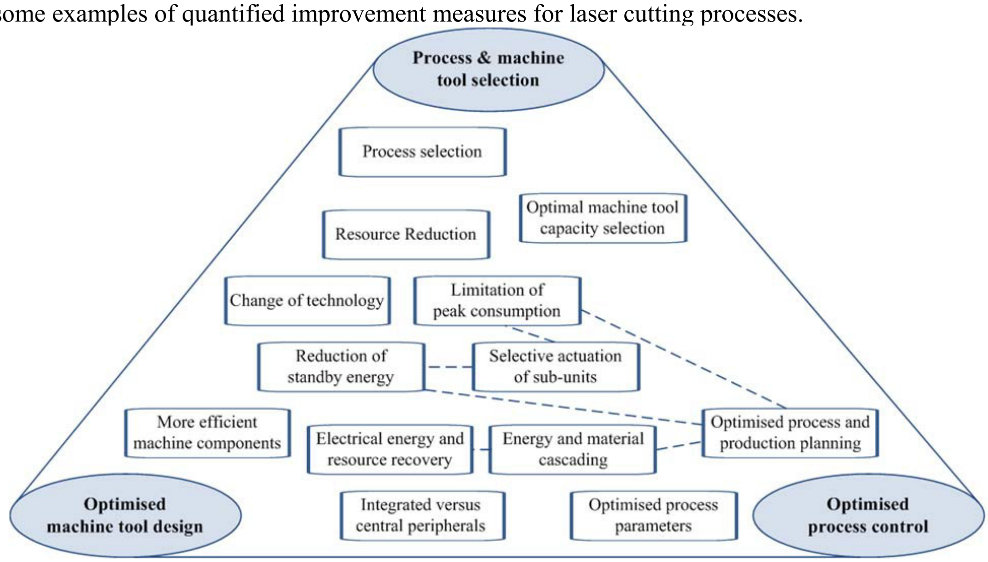


Fig. 6. Improvement measure categories [17].

3.1. Process / Machine tool selection

Figure 7 presents the measured total machine tool input power in function of the requested laser power output for eight CO_2 laser cutting machine tools with different positioning units (e.g. hybrid, flying optics) maximum laser output capacities and sheet dimensions, and shows the importance of proper machine tool selection (near to their maximum capacity) with regard to the power demand. For similar cutting conditions, the largest spread (3kW) can be found for the 4kW CO_2-laser cutting machine tools. The brand dependency is already highlighted in Figure 4.

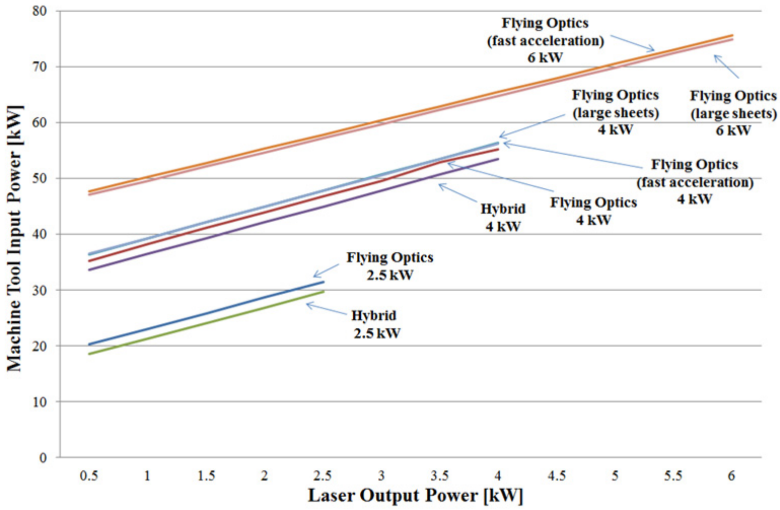


Fig. 7. Machine tool input power consumption as a fuction of the laser output power level for eight different CO_2-laser cutting machine tools.

3.2. More efficient machine tool components

Replacing the individual insulation transformers for steering, drives and laser source sub-units by a single autotransformer with higher efficiency could result in an efficiency increase of around 2%. For a 2.5kW CO_2 laser cutting machine tool this represents an annual energy saving of 360kWh for a single shift production regime.

Last year, Fanuc launched the C series of their CO_2 lasers which are equipped with a high speed rotation turbo blower, driven by a built-in spindle motor, to achieve faster laser gas circulation. For their 4kW sources this means a reduction of 3.9kW at maximum laser output. The related laser source efficiency has increased from 9.7 to 10.8%.

3.3. Change of technology

As shown in Table 1 and Figures 2 to 4, adopting new laser source technologies, such as the new generations of fiber and high brilliance diode lasers, to replace conventional CO_2 lasers, holds the promise of a significant increase in laser source efficiency. Table 3 lists a set of efficiency metrics (at maximum laser power output) for a 2.5kW as well as a 4kW flying optics CO_2 laser, a 2kW fiber laser and the 1.85kW diode laser test setup respectively. Dependent on the machine tool utilization and workshop temperature, the machine tool power demand and related efficiency will vary between both indicated values.

Table 3. Electrical energy efficiency at maximum laser output power.

	CO_2 Laser		Fiber Laser	Diode Laser
Max. Output Power	2.5kW	4kW	2kW	1.85kW
Laser Source	22.7kW	41.1kW	7.8kW	8.0kW
Efficiency	11.0%	9.7%	25.6%	23.1%
Machine Tool[a]	26.3kW	44.8kW	14.3kW	12.1kW
Efficiency	9.5%	8.9%	14.0%	15.3%
Machine Tool[b]	32.9kW	59.3kW	17.6kW	16.4kW
Efficiency Cooling Incl.	7.6%	6.7%	11.4%	11.3%

[a] Compressor(s) and ventilator(s) of laser cooling unit are off.

[b] Compressor(s) and ventilator(s) of laser cooling unit are on at maximum capacity.

3.4. Reduction of standby energy

Next to the efficiency improvement, the new generation of Fanuc laser sources offers two additional standby modes: the “quick power saving” and “eco power saving”. While during the quick power saving mode the discharge is stopped, also the turbo blower is switched off within the eco power saving mode. A reduction of the production ready power demand from 17.8kW (model B) to 14.8kW (model C), or 16.8%, is achieved. Taking into account 15% of standby time [17], the quick power saving and eco power saving mode have a potential reduction in energy consumption of up to 16.0kWh and 18.4kWh per eight hour shift respectively.

3.5. Integrated versus central peripherals

CO_2 laser cutting machine tools use an assist cutting gas (e.g. N_2, O_2 or compressed air) to create an inert or oxidizing atmosphere around the cutting front and to expel molten material. A technical study conducted at KU Leuven investigated the difference between local generation of N_2 and cylinder based N_2 supply. Assuming a consumption of 440m³ (44 cylinders of 50l at 200 bar) N_2 a month, the environmental impact of local N_2 generation is 33% lower than the cylinder based supply.

3.6. Optimized process parameters

From environmental point of view, the laser cutting machine tools should be operated at maximum laser output power (cf. highest laser source efficiency) and the highest achievable cutting speed (cf. lowest cutting time) while respecting the workpiece quality (avoiding dross) and process stability (avoiding loss of cut). From resource point of view, the nesting efficiency should be optimized.

3.7. Selective actuation of sub-units

In order to eliminate no-load losses during off-mode, the transformer(s) can be mechanically switched off. For a 4kW CO_2-laser cutting machine tool these no-load losses account for approximately 300W. Furthermore, also the standby losses of the control unit (80W), drives (80W) and laser source (13W) will be avoided. In total, this measure will save around 473W. Annually, this results in a total saving of 3.2MWh, 2.3MWh and 1.3MWh electricity consumption for a one, two or three shift regime respectively.

Some of the analysed CO_2-laser cutting machine tools are equipped with a winter-off mode. During this off-mode the circulation pump of the cooling system (~3.1kW for a 4kW machine tool) remains active in order to avoid freezing of the coolant. Since industrial experience indicates that the manual summer / winter off-mode switch mainly remains in winter-off mode, a thermostat can be implemented to automatically select the proper off-mode and avoid non-required energy consumption.

3.8. Energy recovery / cascading

With an electrical energy efficiency of around 10%, CO_2 laser sources induce a significant waste heat flow. Since the potential for waste heat recovery at the laser source (which would require re-design) and evaporator (low temperature, 24-28°C, of the cooling water) is rather limited, the opportunity to recover (part of) the waste heat at the condenser of the chiller unit has been analysed in a technical study conducted at KU Leuven. Table 4 lists the quantity of the desuperheating as well as the full condensing waste heat for the different CO_2 laser source types. Although, the values show a relevant potential for energy cascading, it should be noted that the introduction of fiber and diode lasers with more than doubled electrical efficiency, and thus less than half of the waste heat, will reduce the potential environmental benefit of this measure.

Table 4. Waste heat recovery.

CO_2 Laser Source	Duty Cycle	$Q_{desuperheating}$ [kW]	$Q_{fullcondensing}$ [kW]
2.5 kW	50%	3.4	16.6
	75%	4.3	21.0
	100%	5.1	25.5
4 kW	50%	6.3	30.9
	75%	7.9	38.9
	100%	9.5	46.9
6kW	50%	8.8	43.5
	75%	11.0	54.4
	100%	13.3	65.4

4. Conclusions

This paper provides an overview of the state of the art in environmental assessment of laser cutting processes. Besides energy consumption, also the assist gas and generated waste material have a relevant contribution to the environmental impact of CO_2 laser cutting processes. Process emissions and other consumables including spare parts have a rather limited contribution. Derived performance improvement strategies are highlighted and indicate a significant potential to increase the energy and resource efficiency of the different types of laser cutting processes.

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